IJPRA Journal
International Journal of Pharmaceutical research and Applications
Volume 11, Issue 3, May-June 2026, pp:180-194 www.ijprajournal.com ISSN: 2456-4494

Biotechnological valorization of food waste: recent advances, functional ingredients, and circular bioeconomy perspectives

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Date of Submission: 23-04-2026 Date of Acceptance: 03-05-2026

Abstract

Food waste represents a critical global sustainability challenge, with more than 1.3 billion tonnes generated annually. Although discarded, these waste streams retain significant quantities of nutrients and bioactive compounds, offering substantial potential for conversion into high-value functional ingredients. Recent research demonstrates that plant-, animal-, and industrial-based food residues can be valorized using advanced biotechnological approaches. Techniques such as enzymatic hydrolysis, microbial fermentation, supercritical CO_2 extraction, ultrasound-assisted extraction (UAE), and microwave-assisted extraction (MAE) have improved recovery efficiency while reducing solvent usage and environmental burden. Between 2020 and 2025, research trends indicate a shift from single-compound recovery toward integrated biorefinery strategies that enable sequential extraction of multiple value-added products from a single waste stream. Such approaches have been successfully applied to citrus peels, cereal bran, oilseed cakes, whey permeate, fish by-products, and brewery wastes. The recovered ingredients demonstrate broad applications in functional foods, nutraceuticals, cosmetic formulations, and bio-based packaging materials. Environmental assessments further suggest that valorization pathways lower greenhouse gas emissions and reduce reliance on landfilling compared to conventional disposal practices. However, large-scale implementation remains limited by feedstock variability, capital investment requirements, and regulatory complexity, highlighting the need for standardized and economically feasible systems.

Keywords: Food waste valorization; biotechnological processing; functional ingredients; circular bioeconomy; green extraction; enzymatic hydrolysis; microbial fermentation; sustainable food systems.

I. Introduction

Food loss and waste (FLW) has emerged as a major sustainability challenge within global food systems. Approximately 1.3 billion tonnes of food intended for human consumption are lost or wasted annually, corresponding to nearly one-third of total global food production [1]. The environmental implications of this inefficiency are substantial: the global carbon footprint of food wastage has been estimated at approximately 3.3 gigatonnes of CO_2-equivalent per year, alongside the use of nearly 1.4 billion hectares of land and approximately 250 km^3 of freshwater resources [2]. Losses occur across the entire supply chain, from agricultural production and post-harvest handling in low- and middle-income regions to retail and household stages in high-income economies [1,3]. Beyond environmental degradation, FLW represents a significant economic burden. The global economic cost of food wastage has been estimated at nearly USD 1 trillion annually, excluding additional social and ecological externalities [4]. In recognition of these impacts, food waste reduction is embedded within the United Nations Sustainable Development Goal 12.3, which calls for halving per capita food waste at the retail and consumer levels and reducing food losses along production and supply chains by 2030 [3].

While prevention remains a priority, increasing attention has been directed toward valorization strategies that recover value from unavoidable food residues. Food waste valorization involves the transformation of by-products and surplus biomass into value-added materials, including functional ingredients, bioactive compounds, organic acids, and bio-based materials [5,6]. Numerous agro-industrial residues—such as fruit peels, cereal bran, oilseed cakes, and dairy by-products—contain significant amounts of fibers, proteins, lipids, and phenolic compounds that can serve as substrates for biotechnological conversion [6,7].

Advances in green extraction and bioprocessing technologies have expanded the feasibility of food waste valorization strategies. Emerging green extraction methods such as ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction have demonstrated improved extraction efficiency and reduced solvent consumption compared to conventional solvent-based approaches [8]. In parallel, biological processing methods including enzymatic hydrolysis and microbial fermentation have been widely investigated for the conversion of food residues into value-added compounds [5,7]. Within a circular bioeconomy framework, such integrated recovery pathways contribute to resource efficiency, reduce reliance on virgin raw materials, and mitigate environmental impacts associated with disposal [9].

Despite promising technological progress, large-scale implementation remains constrained by feedstock heterogeneity, seasonal variability, regulatory approval requirements for novel ingredients and techno-economic uncertainties [5,9]. Addressing these limitations requires integrated biorefinery models that enable cascading utilization of biomass streams while balancing environmental and economic performance. Given the rapid evolution of food waste biotechnologies, a systematic synthesis of recent advances is essential. This review integrates current knowledge on biotechnological valorization strategies across plant, animal and industrial derived food residues, with emphasis on functional ingredient recovery, process optimization and alignment with circular bioeconomy principles.

II. Global scenario and policy landscape

Food loss and waste (FLW) occurs across all regions of the world; however, its distribution along the supply chain differs markedly between high-income and low- to middle-income countries. In high-income regions, food waste predominantly occurs at retail and household stages, whereas in developing regions, losses are concentrated at production, post-harvest handling, and storage stages [1,3]. Globally, fruits and vegetables represent the most affected commodity group, followed by cereals and animal-derived products [1]. These disparities highlight structural inefficiencies in supply chains and indicate that region-specific technological and policy interventions are required. In Europe, approximately 88 million tonnes of food waste are generated annually, representing substantial environmental and economic burdens [10]. European regulatory efforts, including the 2020 Circular Economy Action Plan, emphasize waste prevention, resource efficiency, and systematic monitoring across member states [11]. Similarly, in the United States, estimates indicate that roughly one-third of the food supply remains unused, prompting policy responses such as the Environmental Protection Agency’s Food Recovery Hierarchy, which prioritizes source reduction, food redistribution, and resource recovery [12].

In many low and middle-income regions, inadequate infrastructure and supply chain inefficiencies contribute substantially to food losses, particularly at production and post-harvest stages [1,13]. Improvements in storage technologies, logistical coordination, and decentralized processing facilities have been identified as critical interventions for loss reduction [13]. Comparable challenges are observed in parts of Sub-Saharan Africa and Latin America, where infrastructural constraints and climatic stressors exacerbate pre-market losses [13]. At the global level, efforts to harmonize measurement and policy implementation are guided by Sustainable Development Goal 12.3, which targets substantial reductions in food waste at retail and consumer levels by 2030. International monitoring frameworks such as FAO’s Food Loss Index and UNEP’s Food Waste Index have improved transparency and cross-national benchmarking, facilitating data-driven policymaking [3]. Increasingly, food waste valorization is being positioned within circular bioeconomy frameworks, linking waste reduction with improved resource efficiency and climate mitigation objectives [14]. Despite these advances, significant challenges remain. Inconsistent definitions of FLW, heterogeneous quantification methodologies, and limited data availability hinder global comparability and policy enforcement [3,15]. Furthermore, regulatory differences governing novel food ingredients and secondary raw materials complicate the commercialization of valorized products. Bridging these gaps requires standardized reporting systems, coordinated policy frameworks and targeted investments to enable large-scale adoption of biotechnological solutions.

III. Valorization of food waste streams

Food waste is generated at multiple stages of the food supply chain, including primary production, processing industries, distribution networks, retail systems, and households. Although these waste streams differ in origin and composition, they share a common characteristic: they are rich in structurally and functionally valuable biomolecules. These include dietary fibers, structural and storage proteins, polyphenolic compounds, lipids, essential fatty acids, vitamins, minerals, and fermentable carbohydrates. Rather than being treated as low-value residues, these materials can serve as renewable feedstocks for biotechnological conversion into functional ingredients and bio-based products. From a circular bioeconomy perspective, valorization refers to the recovery and transformation of such biomass into higher-value applications through physical, chemical, enzymatic, or microbial processes. To provide an integrated understanding, this section consolidates plant-based, animal-based, and industrial food waste streams within a unified valorization framework. Emphasis is placed on the biochemical composition of these materials and the role of modern biotechnological tools in converting heterogeneous waste matrices into standardized, functional outputs suitable for food, feed, nutraceutical, and biorefinery applications.

3.1 Plant-based residues

Plant-based food residues are recognized as promising feedstocks for valorization due to the presence of diverse classes of biomolecules that have potential for recovery as functional ingredients. Reviews on food waste valorization indicate that fruit and vegetable by-products can be sources of antioxidant compounds and dietary fiber, while cereal and legume residues contain significant carbohydrate and protein fractions amenable to further processing [5,6]. Green extraction approaches such as ultrasound-assisted extraction and microwave-assisted extraction have been proposed to recover heat-sensitive phytochemicals from plant matrices with improved efficiency compared to conventional solvent extraction methods [8]. Biotechnological processes including enzymatic treatments and fermentative conversions have also been explored to transform complex plant polymers into more readily usable substances and to enhance the functional properties of recovered fractions [5,7]. Integrated biorefinery frameworks build on these strategies by implementing cascading and sequential recovery steps, enabling multiple product streams to be obtained from a single plant waste feedstock, thereby maximizing resource efficiency and aligning with circular bioeconomy principles [6,16].

3.1.1 Fruit and vegetable wastes

Fruit peels, pomace, seeds, and pulp residues generated from juice, jam, and puree industries represent a significant portion of plant-based food waste streams. These by-products are recognized as rich sources of dietary fiber, phenolic compounds, carotenoids, organic acids and residual sugars, which provide considerable potential for recovery as value-added ingredients [5,6,17]. Due to their phytochemical richness, fruit and vegetable wastes have been widely investigated for biotechnological recovery. Green extraction technologies such as ultrasound-assisted extraction (UAE) and supercritical fluid extraction (SFE) have been applied to improve mass transfer efficiency, enhance recovery of antioxidant compounds, and reduce solvent consumption compared with conventional extraction techniques [18,19]. In addition, microbial fermentation using lactic acid bacteria and fungal strains has been explored to modify plant cell wall structures and promote the release of bound phenolic compounds from fruit matrices. Such treatments have been associated with improvements in antioxidant activity and functional properties of derived ingredients [7,20]. Common fruit residues investigated for valorization include apple pomace, citrus peel, banana peel, grape pomace, and mango peel. These substrates have been utilized for the production of pectin-rich extracts, antioxidant fractions, functional dietary fibers, carotenoid-containing powders, and natural colorants suitable for food and nutraceutical applications [5,6]. Overall, fruit and vegetable waste streams demonstrate strong potential for conversion into multiple functional ingredients within integrated biorefinery systems aligned with circular bioeconomy principles.

3.1.2 Cereal and legume wastes

Processing of cereals and legumes generates substantial quantities of by-products such as rice bran, wheat bran, brewer's spent grain (BSG), and legume hulls. These residues are recognized as nutritionally dense matrices containing proteins, β-glucans, arabinoxylans, tocols, and phenolic acids, particularly bound ferulic acid in cereal bran fractions [7,21].

Due to their compositional richness, cereal and legume residues have been investigated as promising substrates for the development of functional ingredients. Enzymatic hydrolysis employing proteases and carbohydrases has been used to release bioactive peptides from cereal proteins. Several studies report that such peptides exhibit antioxidant and antihypertensive activities in in vitro systems [22,23]. Brewer's spent grain, one of the most abundant agro-industrial residues from beer production, has been extensively studied for its fiber and protein recovery potential. Fermentation and enzymatic treatments have been explored to modify its insoluble fiber fractions and enhance functional properties for incorporation into bakery and cereal-based products [7,24].

Microwave-assisted and other assisted extraction techniques have also been applied to cereal bran to improve the recovery of bound phenolic acids, including ferulic acid, compared with conventional solvent extraction methods [18,21]. Similarly, combined thermal and enzymatic treatments of legume hulls have been reported to enhance protein digestibility and increase nutrient accessibility. Collectively, these valorization approaches demonstrate that cereal and legume by-products can serve as cost-effective raw materials for producing dietary fibers, bioactive peptides, and antioxidant-rich extracts suitable for functional food applications.

3.2 Animal-based residues

Animal-based residues are generated from meat, fish, dairy, and egg processing industries and represent a diverse group of biologically rich waste streams. These materials typically contain collagen, gelatin, bioactive peptides, omega-3 fatty acids, whey proteins, lactose, and essential minerals, making them valuable substrates for biotechnological applications and functional ingredient development [25,26]. Unlike many plant-derived residues, animal by-products often require pretreatment steps such as thermal processing, enzymatic hydrolysis, fat removal, or membrane separation to facilitate the recovery of functional biomolecules. Fish skin, scales, and bones are widely processed for the extraction of collagen and gelatin, which can subsequently be hydrolyzed into low-molecular-weight peptides exhibiting antioxidant and other biological activities in vitro [25,27]. Dairy by-products, particularly whey and whey permeate, are rich in lactose and high-quality proteins. Through fermentation and membrane technologies such as ultrafiltration and nanofiltration, whey components can be converted into bioactive peptides, lactose-derived prebiotics, and protein concentrates suitable for food and nutraceutical applications [22,28]. Similarly, meat-processing residues containing connective tissue proteins can be enzymatically hydrolyzed to produce protein hydrolysates with improved functional properties for incorporation into food and feed formulations [26]. Collectively, these valorization strategies demonstrate that animal-based residues can be transformed into high-value ingredients for nutraceutical, cosmetic, and biomedical applications while contributing to waste reduction and circular resource utilization.

3.2.1 Fish and seafood wastes

Waste generated during fish processing, including heads, bones, viscera, skin, and scales, represents a substantial fraction of total biomass and is recognized as a rich source of high-value biomolecules [25,27]. These by-products contain bioactive peptides, collagen, gelatin, chitin, and long-chain omega-3 fatty acids, making them promising substrates for nutraceutical and functional ingredient development. Enzymatic hydrolysis using proteolytic enzymes such as alcalase, flavourzyme and neutrase has been widely employed to generate peptide fractions from fish proteins. Fish protein hydrolysates have been reported to exhibit antioxidant and antimicrobial activities in vitro, supporting their potential application in functional foods and health-oriented formulations [27,29]. Controlled hydrolysis improves solubility and bioavailability of resulting peptides, enhancing their technological and functional performance.

Fish skin and scales are important alternative sources of collagen and gelatin. These materials can be extracted and further hydrolyzed to produce low-molecular-weight collagen peptides with improved functional properties compared with native collagen [25]. Crustacean shell wastes, naturally rich in chitin, can be converted into chitosan through chemical deacetylation or biotechnological processes. Chitosan is a versatile biopolymer used in food preservation, biodegradable films, water clarification, and biomedical applications due to its antimicrobial and film-forming properties [30]. Additionally, fish processing residues are significant sources of omega-3 fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). Lipid extraction and refinement processes have been developed to recover fish oils for encapsulation, functional food enrichment, and dietary supplementation [31]. Overall, these valorization strategies demonstrate that fish and seafood waste streams can be converted into bioactive peptides, collagen derivatives, chitosan-based materials, and omega-3 enriched products, contributing to circular resource utilization and reduction of marine processing waste.

3.2.2 Dairy wastes

Whey is the primary by-product generated during cheese and paneer production and represents a major fraction of dairy processing residues. Although historically considered a waste stream, whey is now recognized as a nutrient-rich matrix containing high-quality proteins, lactose, minerals, and bioactive peptides, making it an important substrate for functional ingredient development [28]. Membrane technologies such as ultrafiltration and nanofiltration are widely employed to concentrate whey proteins and isolate whey protein concentrates (WPC) and whey protein isolates (WPI). Enzymatic hydrolysis of whey proteins has been used to generate bioactive peptide fractions exhibiting antioxidant, antihypertensive, and immunomodulatory activities in vitro [22,32]. Hydrolysis also improves digestibility and functional properties of whey-derived ingredients.

In addition to protein recovery, lactose-rich permeate obtained during membrane filtration can be valorized through fermentation processes. Lactose has been converted into galacto-oligosaccharides (GOS), recognized as prebiotic compounds that promote beneficial gut microbiota [33]. Fermentative pathways have also been explored for the production of lactic acid and other value-added metabolites from whey streams. Processed whey fractions are commonly incorporated into sports nutrition formulations, infant formula, and functional beverages due to their high nutritional quality and techno-functional properties [28]. Overall, valorization of dairy wastes enables the production of protein concentrates, bioactive peptides, and prebiotic ingredients while mitigating the environmental burden associated with whey disposal.

3.2.3 Meat processing residues

Meat processing generates substantial quantities of solid residues, including bones, tendons, cartilage, and connective tissues. These materials are rich in collagen, gelatin, minerals, and structural proteins, making them suitable substrates for valorization rather than disposal [26].

Collagen extraction from meat by-products can be achieved through thermal or enzymatic treatments. Enzyme-assisted extraction has gained attention because it operates under comparatively mild conditions, which may help preserve structural integrity and functional properties of collagen compared with harsh thermal processing [25,26]. Such approaches are being explored as part of more sustainable recovery systems within the meat processing sector. Gelatin and collagen hydrolysates derived from meat residues are widely used to improve food texture, stabilize emulsions, and encapsulate bioactive compounds. They are also incorporated into nutraceutical and biomedical formulations due to their film-forming and gelling properties [25]. Bone residues represent another valuable fraction of meat-processing waste. After cleaning and controlled heat treatment, bones can be processed into calcium-rich powders and mineral supplements, contributing to mineral recovery and circular use of resources [26]. Overall, these strategies demonstrate that meat-processing by-products can be converted into functional ingredients and structural biomaterials while mitigating the environmental burden associated with disposal.

3.3 Industrial by-products

Industrial food processing generates concentrated and compositionally consistent by-product streams that often retain substantial amounts of nutrients, bioactive compounds, and structural biomolecules. Examples include oilseed cakes from oil extraction industries, brewer's spent grain from breweries, grape pomace from wineries, and residues from sugar and starch processing [5,7]. Compared with retail or household waste, industrial by-products are generated in relatively homogeneous and traceable batches, facilitating collection, standardization, and large-scale valorization. Oilseed cakes, for example, remain rich in proteins and phenolic compounds after oil removal, while winery residues retain polyphenols and dietary fiber fractions [5].

Modern biotechnological approaches such as enzymatic hydrolysis, membrane separation, fermentation, and assisted extraction techniques have been employed to convert industrial residues into functional fibers, protein isolates, antioxidant extracts, organic acids, and biopolymers [6,7]. Integrated biorefinery frameworks have increasingly been proposed to enable sequential recovery of multiple value-added components from a single biomass stream, thereby improving economic viability and resource efficiency [6]. Overall, industrial food processing by-products represent strategically favorable substrates for scalable valorization. Their systematic reuse contributes to circular bioeconomy models and reduces the environmental burden associated with disposal of high-volume industrial residues.

3.3.1 Oilseed and nut industry by-products

Oilseed cakes generated after mechanical pressing or solvent extraction represent protein-rich by-products that retain substantial residual nutrients following oil removal. These materials are widely recognized as promising substrates for biotechnological applications due to their residual protein content and associated bioactive compounds [34]. Because they are produced in large and relatively uniform batches, oilseed processing residues are particularly suitable for large-scale valorization. Protein recovery from oilseed cakes is commonly achieved through alkaline extraction followed by isoelectric precipitation or enzymatic hydrolysis. Such treatments modify solubility and improve functional properties such as emulsifying and foaming capacity, enhancing their suitability for incorporation into beverages, bakery formulations, and plant-based food systems [6,34].

Certain oilseed residues, particularly flaxseed and sesame cakes, are known to contain lignan compounds that have been investigated for their antioxidant properties [35]. In addition to protein and lignan recovery, supercritical CO_2 extraction has been applied in oilseed and nut industries to obtain residual oils enriched in unsaturated fatty acids and naturally occurring antioxidant compounds while minimizing solvent residues [36]. Nut shells and seed coats, although less extensively explored, have demonstrated potential as sources of phenolic-rich extracts when subjected to assisted and green extraction approaches [6]. Overall, oilseed and nut industry by-products provide multiple valorization pathways, including the production of functional protein ingredients, specialty oils, and bioactive extracts suitable for food, nutraceutical, and cosmetic applications, while contributing to resource efficiency and circular bioeconomy strategies.

3.3.2 Beverage and brewing wastes

Beverage and brewing industries generate substantial quantities of by-products, including brewer’s spent grain, brewer’s spent yeast, and grape pomace from winemaking. These residues contain valuable compounds such as β-glucans, mannoproteins, polyphenols, and natural pigments, making them attractive substrates for valorization [5,7]. Brewer’s spent yeast is particularly rich in cell wall polysaccharides, including β-glucans and mannoproteins. Controlled autolysis or enzymatic treatments are commonly applied to release mannoproteins, which have been investigated for their stabilizing and emulsifying properties in food and beverage systems [37]. These compounds contribute to improvements in mouthfeel and foam stability in fermented products. Grape pomace, a by-product of wine production consisting of skins, seeds, and stems, is a significant source of phenolic compounds, including proanthocyanidins and anthocyanins [38]. These extracts have been studied for incorporation into functional food formulations due to their antioxidant properties. Pigments derived from grape skins have also been explored as natural colorants in clean-label food applications [6]. In addition to ingredient recovery, yeast and grape pomace fractions have been evaluated as substrates for fermentation processes and as reinforcing agents in biodegradable packaging materials [5]. Overall, by-products from beverage and brewing industries offer multiple valorization opportunities, enabling the production of high-value ingredients while contributing to waste reduction within fermentation-based industries.

3.3.3 Sugar and starch industry wastes

Sugar and starch processing industries generate large volumes of residues such as molasses, bagasse, and potato peels, all of which contain substantial amounts of fermentable sugars and structural carbohydrates. Molasses, a concentrated by-product of sugar refining, is widely utilized as a substrate for microbial fermentation processes for the production of bioethanol and organic acids due to its high sugar content and availability [7]. Potato peels, which contain starch, non-starch polysaccharides, and soluble sugars, have been investigated as potential substrates for biotechnological conversion and enzyme-assisted recovery processes aimed at producing value-added compounds [39]. Bagasse, derived from sugarcane crushing, is primarily composed of cellulose, hemicellulose, and lignin, and has been explored both as a fermentation substrate and as a source of dietary fiber [40]. To improve the accessibility of fermentable components in lignocellulosic residues such as bagasse, pre-treatment strategies including steam explosion and alkaline hydrolysis have been widely investigated to enhance enzymatic digestibility [40]. Collectively, these valorization strategies demonstrate how sugar- and starch-based processing residues can be converted into diverse bioproducts, contributing to resource recovery and sustainable industrial practices.

3.4 Integrated biorefinery approaches

Integrated biorefinery approaches represent an advanced direction in food-waste valorization, enabling the sequential or parallel recovery of multiple high-value products from a single waste stream. Rather than targeting only one compound, biorefineries operate through cascading processing schemes in which each biochemical fraction of the raw material is utilized, thereby enhancing resource efficiency and reducing residual waste generation [5,6].

For example, citrus-processing residues can undergo steam distillation to recover essential oils rich in limonene, followed by acid or enzymatic extraction of pectin from the remaining solid matrix. Subsequent processing steps may focus on flavonoid recovery, dietary fiber concentrates, or fermentation of carbohydrate fractions into bio-based products. Such multiproduct extraction models improve the economic feasibility of citrus waste valorization by generating several marketable outputs from a single feedstock [6]. Similarly, cereal-processing wastes such as bran and other milling residues are suitable substrates for integrated biorefineries due to their content of phenolic compounds, fibers, proteins, and residual lipids. Sequential extraction strategies have been proposed in which antioxidants and phenolic acids are recovered first, followed by isolation of protein and fiber fractions, and finally conversion of carbohydrate-rich residues into bioethanol or organic acids via fermentation [7,40].

Fish-processing industries have also explored biorefinery models to manage skins, bones, scales, and viscera. Enzymatic hydrolysis is typically applied to generate collagen, gelatin, and protein hydrolysates, after which lipid fractions rich in omega-3 fatty acids can be separated. Mineral-rich residues may be further processed for calcium recovery or agricultural applications [25,27]. Overall, integrated biorefinery systems transform food waste from a single-compound extraction framework into a comprehensive resource-utilization platform. By combining environmental sustainability with economic value generation, such systems are increasingly recognized as central components of circular bioeconomy strategies.

Table 1: Major food waste categories and their valorization potential

Food waste category	Principal recoverable components	References
Fruit and vegetable processing residues	Phenolic compounds, dietary fiber, pectin	[6]
Cereal and grain processing by-products	Fiber-rich fractions, proteins	[7]
Oilseed processing residues	Proteins, residual oils	[34]
Fish and marine processing residues	Collagen, fish oils	[31]
Dairy processing by-products	Whey proteins, lactose	[28]
Fermentation industry residues	Yeast biomass, bioactive compounds	[7]
Sugar and starch processing residues	Fermentable agro-industrial residues	[40]

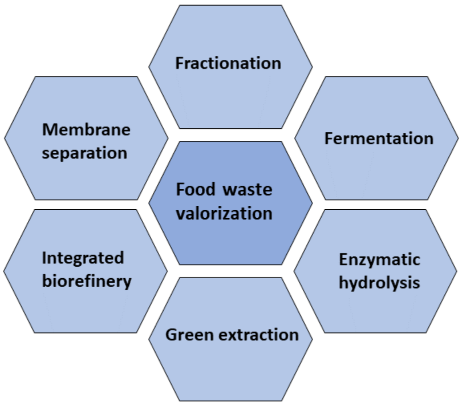

Figure 1: Integrated processing routes

IV. Applications of functional ingredients derived from food waste

The biotechnological valorization of food waste enables the recovery of diverse functional ingredients with applications across food, nutraceutical, pharmaceutical, and cosmetic industries. These recovered compounds include dietary fibers, bioactive peptides, polyphenols, carotenoids, prebiotic oligosaccharides, organic acids, essential oils, and biopolymers [5,6]. Owing to their techno-functional and nutritional properties, these ingredients are increasingly incorporated into value-added formulations. The following subsections discuss major application areas in detail.

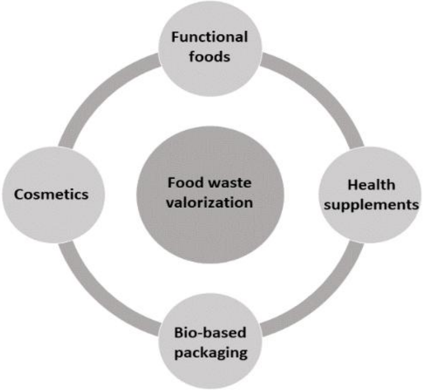

Figure 2: Key application domains

4.1 Functional food applications

Functional foods represent a rapidly expanding market for ingredients derived from food-waste streams, driven by consumer demand for clean-label and nutrient-enriched products. Plant-based fibers recovered from fruit pomace, cereal bran, and vegetable residues have been incorporated into baked goods, beverages, and dairy alternatives due to their water-binding capacity, textural enhancement, and fat-replacement potential [5,6]. Pectin extracted from citrus and apple processing by-products remains widely utilized as a gelling, stabilizing, and emulsifying agent in jams, sauces, and reduced-sugar formulations. Similarly, modified dietary fibers contribute to viscosity improvement and development of lower-calorie food products [6]. Polyphenols and carotenoids derived from fruit and vegetable residues such as grape pomace and tomato skins have been explored as natural antioxidants and colorants in clean-label foods. These bioactive compounds have demonstrated the ability to delay lipid oxidation and improve oxidative stability in model food systems [38].

In addition, protein hydrolysates and bioactive peptides generated from cereal, dairy, and marine processing residues have been investigated for incorporation into functional beverages and protein-enriched products. Several studies report antioxidant and antihypertensive activities of such peptides in vitro, supporting their potential inclusion in health-oriented food formulations [22,27]. Collectively, these applications highlight the role of waste-derived ingredients in supporting nutritional enhancement, improved functionality, and clean-label product development within the functional food sector.

4.2 Nutraceutical and supplement applications

The nutraceutical sector has expanded significantly in response to consumer demand for natural and minimally processed health-oriented products. Polyphenols extracted from fruit and vegetable residues—including phenolic acids, flavonoids, and proanthocyanidins—have attracted interest due to their documented antioxidant capacity and potential physiological relevance [6,38]. These compounds are incorporated into capsules, powdered supplements, and functional beverages aimed at supporting oxidative balance. Fish-processing by-products contribute substantially to nutraceutical formulations through the recovery of collagen peptides and omega-3 fatty acids. Collagen hydrolysates derived from marine residues have been widely explored for incorporation into joint- and skin-health products [25], while marine lipid fractions enriched in long-chain polyunsaturated fatty acids remain established components of dietary supplements [27].

Prebiotic oligosaccharides such as galacto-oligosaccharides (GOS), xylo-oligosaccharides (XOS), and mannan-oligosaccharides (MOS), which can be generated through enzymatic or fermentative processing of dairy and cereal residues, have been investigated for their ability to modulate gut microbiota by selectively promoting beneficial bacterial populations [33]. These ingredients are increasingly incorporated into synbiotic products, infant formulations, and digestive health supplements. Overall, bioactive compounds derived from food-processing residues represent an important resource base for the nutraceutical industry, supporting sustainable ingredient sourcing alongside functional product development.

4.3 Prebiotic ingredients and gut health applications

Prebiotic fibers derived from citrus residues, apple pomace, cereal brans, and brewer’s spent grains have attracted increasing interest due to their potential roles in modulating gut microbiota composition. These materials contain soluble pectins, arabinoxylans, resistant starch, and various oligosaccharides that can undergo microbial fermentation in the colon [6,33].

During fermentation, such fibers are converted by intestinal microbiota into short-chain fatty acids (SCFAs), including acetate, propionate, and butyrate, which are associated with improved gut microbial activity and maintenance of intestinal homeostasis [33]. In vitro and simulated gastrointestinal studies have demonstrated that waste-derived fibers can enhance SCFA production and selectively promote beneficial bacterial groups.Galacto-oligosaccharides (GOS) generated from dairy permeate and xylo-oligosaccharides (XOS) obtained from cereal residues are among the most widely studied prebiotic oligosaccharides. These compounds have been incorporated into yogurts, infant formulations, and synbiotic products due to their documented ability to stimulate Bifidobacterium and Lactobacillus populations [33]. Overall, prebiotic ingredients recovered from food-processing residues represent sustainable alternatives to conventional sources, contributing both functional value and circular resource utilization within gut-health-focused product development.

4.4 Natural antioxidants and preservatives

Natural antioxidants recovered from grape seeds, pomegranate peel, mango peel, and herb-processing residues have been widely investigated as clean-label alternatives to synthetic preservatives, particularly in foods susceptible to lipid oxidation

[6,38]. These extracts are typically rich in phenolic acids, flavonoids, and tannins, which contribute to radical-scavenging and metal-chelating activities. Studies conducted in model and real food systems have shown that phenolic-rich extracts from agro-industrial by-products can delay lipid oxidation and improve oxidative stability in meat, dairy, and bakery products. Their incorporation may also influence color stability and certain sensory characteristics depending on formulation and concentration [38]. Essential oils obtained from citrus peels and herb-processing residues have also been evaluated for antimicrobial activity against spoilage microorganisms and selected foodborne pathogens. Their application in natural preservation systems—including edible coatings, active packaging films, and surface treatments—has been increasingly explored as part of clean-label preservation strategies [41]. Encapsulation and delivery technologies are being investigated to enhance the stability, reduce volatility, and enable controlled release of these bioactive compounds in food matrices. Overall, waste-derived antioxidants and antimicrobial agents represent promising sustainable ingredients for improving product stability and supporting clean-label food preservation approaches.

4.5 Cosmetic and personal care applications

Food-waste-derived ingredients have attracted increasing interest in cosmetic and personal care applications, reflecting industry demand for sustainable and naturally sourced active compounds. Collagen peptides and gelatin extracted from fish skins, bones, and scales have been explored for use in skincare formulations due to their amino acid composition and film-forming properties [25]. Marine-derived collagen hydrolysates are incorporated into creams and serums, where they are investigated for their moisturizing and structural-support potential.

Polyphenols obtained from grape and berry processing residues have been examined for inclusion in topical formulations due to their antioxidant properties and ability to scavenge reactive oxygen species [41]. Such extracts are increasingly considered in protective and anti-oxidative skincare products.

Pectin and cellulose derivatives recovered from fruit and vegetable residues function as biodegradable thickening agents, stabilizers, and rheology modifiers in personal care formulations, providing alternatives to synthetic polymers [6]. Lactic acid produced via microbial fermentation of sugar- and starch-based residues is widely utilized in cosmetic applications as a pH adjuster and exfoliating agent. Its humectant characteristics make it a common component of moisturizing and resurfacing formulations [42]. Collectively, these valorized bio-derived ingredients illustrate the expanding role of food-processing residues in high-value cosmetic applications aligned with sustainability objectives.

4.6 Bio-based packaging and edible coatings

Bio-based packaging materials and edible coatings derived from food-processing residues have attracted considerable interest as sustainable alternatives to petroleum-based plastics. Biopolymers such as pectin, chitosan, alginate, cellulose, and starch derivatives recovered from fruit residues, seafood shells, and starchy by-products can be processed into biodegradable films and coatings with functional barrier and mechanical properties suitable for food-packaging applications [6,41]. These biomaterials may exhibit oxygen and moisture barrier characteristics depending on formulation and processing conditions. In particular, chitosan and certain polysaccharide-based films have been investigated for their inherent antimicrobial properties and biodegradability, making them attractive for eco-friendly packaging systems. Edible coatings prepared from citrus pectin, starch-based materials, or chitosan derived from seafood shells have been studied for application on fresh fruits and vegetables to reduce moisture loss, delay oxidative changes, and limit surface microbial growth. Incorporation of natural antioxidants or essential oils into such matrices has been explored to enhance preservation performance and functional stability. Overall, waste-derived biopolymers present promising opportunities for the development of sustainable packaging systems aligned with circular bioeconomy principles, while contributing to reduced reliance on conventional synthetic polymers.

V. Environmental and economic aspects of food waste valorization

Food waste valorization plays an increasingly important role in reducing the environmental burdens associated with conventional disposal practices while enhancing resource efficiency within food systems. When organic food waste is landfilled, it undergoes anaerobic decomposition and generates methane, a greenhouse gas with substantially higher global warming potential than carbon dioxide [1]. As a result, landfill diversion represents a major climate-mitigation opportunity. Comparative life-cycle assessment (LCA) studies consistently indicate that recovery-oriented management options—such as anaerobic digestion and composting—generally exhibit lower environmental impacts than landfill disposal. These systems enable energy recovery, nutrient recycling, and reduced greenhouse gas emissions when properly implemented [43]. Anaerobic digestion, in particular, converts organic residues into biogas and digestate, supporting renewable energy production and circular nutrient flows.

Beyond emissions reduction, valorization contributes to broader resource-conservation goals. Recovery of functional components—including dietary fibers, polyphenols, proteins, lipids, and biopolymers—from agro-industrial residues reduces reliance on virgin raw materials and promotes circular use of biomass [6]. Similarly, assessments of food manufacturing waste management demonstrate that valorization options can provide environmental advantages compared with disposal-based systems [5]. Food-processing residues often exhibit high biological oxygen demand (BOD) and can contribute to water pollution if inadequately treated. Approaches that stabilize or convert organic fractions into useful products reduce pollutant loads and mitigate risks associated with leachate formation and uncontrolled degradation [44]. Such strategies align with circular-economy models that emphasize waste prevention, material recovery, and regenerative resource cycles.

From an economic standpoint, valorization transforms low- or negative-value waste streams into commercially relevant products. The extraction of specialty ingredients, bioactive compounds, and bio-based materials creates additional revenue streams and may offset disposal costs [6]. Integrated biorefinery concepts further enhance economic feasibility by enabling multiple products to be generated from a single feedstock, thereby maximizing resource efficiency [5]. However, economic viability depends on technological maturity, capital investment, supply-chain coordination, and market acceptance. Variability in waste composition, infrastructure limitations, and regulatory requirements can affect scalability. Despite these challenges, continued technological advancement and supportive policy frameworks are expected to strengthen the role of valorization in sustainable resource management. Overall, food waste valorization offers clear environmental benefits and economic potential when implemented within well-designed recovery systems. Its success depends on integration of technological innovation, life-cycle thinking, and circular bioeconomy principles.

VI. Challenges, limitations, and regulatory barriers in food waste valorization

The large-scale implementation of food waste valorization is constrained by scientific, technological, economic, regulatory, and logistical challenges. One of the most significant scientific limitations is the heterogeneity of food waste streams. The composition of food residues varies considerably depending on crop type, seasonal fluctuations, agricultural practices, processing methods, and storage conditions. As a result, concentrations of polyphenols, proteins, lipids, fibers, and micronutrients may differ substantially across batches, complicating process standardization and consistent product quality. Such compositional variability remains a major barrier to reproducibility and industrial scalability [5,45]. High moisture content and nutrient availability further make food waste highly perishable and susceptible to microbial spoilage. Without proper segregation, storage, and cold-chain management, degradation reduces extraction yield and functional quality while increasing safety risks [1,46]. These challenges are particularly pronounced in regions lacking organized waste collection systems.

Technological constraints also limit industrial adoption. Although advanced extraction and bioconversion techniques—such as enzyme-assisted extraction, ultrasound-assisted extraction, microwave-assisted extraction, and fermentation—show high efficiency at laboratory scale, their industrial deployment requires substantial capital investment, process optimization, solvent recovery systems, and purification infrastructure [6]. Integrated biorefinery models, which aim to recover multiple fractions sequentially from a single waste stream, enhance resource efficiency but demand coordinated process design and specialized technical expertise [5]. Consequently, small and medium-sized enterprises may struggle to implement such complex systems. Economic feasibility is another critical determinant. Initial installation costs for bioreactors, membrane filtration systems, drying technologies, and downstream purification units are high, and return on investment depends on stable feedstock supply and established markets for valorized products. Circular economy analyses emphasize that financial risk and uncertain market conditions remain significant obstacles to scaling waste-to-resource systems [45].

Regulatory requirements introduce additional complexity. Ingredients derived from food waste must meet stringent safety standards concerning microbiological quality, heavy metals, pesticide residues, allergens, and chemical contaminants. In the European Union, the authorization of novel food ingredients is regulated under Regulation (EU) 2015/2283, which requires a comprehensive safety assessment, including toxicological evaluation, before market approval [47]. In the United States, ingredients may be evaluated under the Generally Recognized as Safe (GRAS) framework administered by the U.S. Food and Drug Administration (FDA), wherein safety must be demonstrated either through scientific procedures or a history of safe use [48]. These regulatory processes require substantial scientific documentation, and differences between regional frameworks can increase time, cost, and uncertainty for companies pursuing international commercialization. Logistical challenges further hinder effective implementation.

Food waste is generated from decentralized sources including households, retail outlets, food service establishments, and processing facilities. Mixed waste streams often contain non-food materials, increasing sorting and preprocessing costs while reducing feedstock purity. Life-cycle assessments of municipal food waste systems highlight that inefficient collection and transport structures can negatively affect environmental and economic performance [44]. Taken together, scientific variability, technological scale-up limitations, economic constraints, regulatory complexity, and logistical inefficiencies explain why food waste valorization—despite strong environmental and economic potential—remains challenging at commercial scale. Addressing these barriers will require technological innovation, infrastructure development, regulatory harmonization, and improved coordination across supply chains.

VII. Future prospects and strategic directions in food waste valorization

Future advancement in food waste valorization will increasingly depend on the integration of green chemistry principles, scalable biorefinery platforms, digital optimization tools, and harmonized regulatory frameworks. As circular bioeconomy strategies gain global attention, research focus is shifting from single-compound recovery toward cascading biorefinery systems capable of generating multiple high-value products from a single biomass stream [49,50]. Such integrated models enable sequential extraction of fibers, proteins, phenolics, organic acids, and bioenergy fractions, thereby maximizing resource efficiency while minimizing residual waste. Green extraction technologies are expected to dominate next-generation industrial systems. Supercritical CO_2 extraction has demonstrated high efficiency in recovering lipophilic compounds from agro-industrial residues while avoiding harmful organic solvents [36]. Pressurized liquid extraction and microwave-assisted extraction reduce solvent use and processing time, improving sustainability metrics [51].

More recently, natural deep eutectic solvents (NADES) have emerged as promising green media for selective extraction of bioactive compounds, offering improved biodegradability and reduced toxicity [52,53]. The transition from batch processes to continuous-flow and intensified extraction systems will further enhance industrial scalability. Digital transformation represents another critical direction. Artificial intelligence and machine learning models are increasingly applied in food processing and supply-chain systems to optimize fermentation processes, predict extraction yields, and manage biomass variability in real time [54,55]. These tools enable improved process control, reduced material loss, and better decision-making under variable feedstock conditions. Blockchain-based traceability systems are also under development to improve transparency in agri-food supply chains and strengthen consumer trust in upcycled ingredients [56,57]. Integration of metabolomics and chemometric modeling will further assist in standardizing heterogeneous waste feedstocks and improving reproducibility.

From a sustainability assessment perspective, future development must integrate life-cycle assessment (LCA) with techno-economic analysis (TEA). Combined LCA–TEA frameworks provide a comprehensive approach for simultaneously evaluating environmental impacts and financial feasibility, enabling informed decision-making during scale-up of bio-based processing systems [58,59]. Such integrated assessments are essential to determine whether valorization pathways offer genuine environmental and economic advantages compared to conventional waste disposal or fossil-based production systems. Industrial symbiosis and cross-sector collaboration will also shape the field. Circular economy research highlights the importance of resource-sharing networks between food processors, bioenergy facilities, and biochemical manufacturers to reduce cost and improve material efficiency [60,61]. These collaborative ecosystems stabilize feedstock supply and distribute infrastructure investment across multiple stakeholders. Regulatory evolution will remain central to long-term expansion. In the European Union, Regulation (EU) 2015/2283 on Novel Foods establishes the scientific requirements for authorizing new food ingredients [47]. Continued development of science-based risk assessment approaches will be necessary to facilitate innovation while maintaining consumer safety. Harmonization across international regulatory bodies would significantly reduce commercialization uncertainty.

Finally, consumer perception is likely to evolve alongside growing environmental awareness. Studies in sustainable consumption demonstrate that transparent labeling, environmental communication, and trust-building mechanisms increase acceptance of bio-based and circular economy products [62,63]. Effective communication strategies will therefore be essential for mainstream adoption of waste-derived functional ingredients. Overall, the convergence of green chemistry innovation, digital technologies, integrated sustainability assessment, industrial collaboration, and progressive regulatory frameworks positions food waste valorization as a cornerstone of future bio-based economies. With coordinated interdisciplinary research and policy support, valorization systems are expected to transition from niche sustainability initiatives to mainstream industrial practice.

VIII. Conclusion and recommendations

Food waste valorization has evolved from a conceptual sustainability strategy into a scientifically and industrially relevant pathway aligned with circular bioeconomy objectives. The growing recognition of the environmental burden associated with conventional waste disposal has accelerated research and industrial interest in converting food residues into value-added products. As discussed throughout this review, valorization contributes to greenhouse gas mitigation, improved resource efficiency, nutrient recycling, and diversion of organic waste from landfills. From an economic perspective, the recovery of high-value compounds—including polyphenols, dietary fibers, bioactive peptides, functional oils, organic acids, and biopolymers—creates new revenue streams while simultaneously reducing disposal costs. The transition from single-product extraction models toward integrated biorefinery systems enhances economic feasibility by maximizing resource utilization. Technological advancements in green extraction, enzymatic processing, fermentation systems, and digital monitoring platforms have further strengthened the scalability and efficiency of valorization pathways.

Despite this progress, several barriers continue to limit large-scale implementation. Variability in raw material composition, technological scale-up challenges, high capital investment requirements, fragmented supply chains, and inconsistent regulatory frameworks remain significant obstacles. In addition, consumer perception of waste-derived ingredients continues to influence market penetration, underscoring the need for improved transparency, labeling strategies, and public communication. Future development should prioritize integrated and data-driven valorization systems capable of maintaining economic viability while ensuring environmental performance. Multiproduct biorefineries should form the foundation of industrial planning. The incorporation of digital tools—including artificial intelligence, process-monitoring technologies, and traceability systems—can enhance operational stability, safety, and supply-chain transparency. Collaboration among food manufacturers, biotechnology firms, waste management entities, policymakers, and research institutions will be essential to establish reliable infrastructure and long-term commercial success.

Strengthening regulatory harmonization, improving quality-standard frameworks, and providing targeted financial incentives will be critical to accelerate industrial adoption. Increasing consumer trust through certification systems, scientific validation, and sustainability labeling can further support market acceptance. In conclusion, food waste valorization stands at a pivotal stage characterized by strong scientific validation and expanding industrial relevance. With coordinated technological innovation, policy support, and stakeholder collaboration, food residues can transition from being considered waste to becoming strategic bio-based resources that contribute meaningfully to environmental protection, economic resilience, and sustainable resource management.

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